

LOFAR: A NEW RADIO TELESCOPE FOR LOW FREQUENCY RADIO OBSERVATIONS: SCIENCE AND PROJECT STATUS

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LOFAR, the Low Frequency Array, is a large radio telescope consisting about 100 soccer field sized antenna stations spread over a region of 400 km in diameter. It will operate in the frequency range from ~ 10 to 240 MHz, with a resolution at 240 MHz of better than an arcsecond. Its superb sensitivity will allow for a broad range of astrophysical studies. In this contribution we first discuss four major areas of astrophysical research in which LOFAR will undoubtedly make important contributions: reionisation, distant galaxies and AGNs, transient radio sources and cosmic rays. Subsequently, we will discuss the technical concept of the instrument and the status of the LOFAR project.

1. Introduction

LOFAR, the Low Frequency Array, is a large radio telescope that will open up the virgin territory of observations at low radio frequencies for a broad range of astrophysical studies. It will observe the Universe at frequencies from ~ 10 to 240 MHz (corresponding to wavelengths of 30 to 1.5 m) with a resolution at 240 MHz of better than one arcsecond. Its superb sensitivity and high resolution will be a dramatic improvement over previous facilities at these wavelengths. It is only with recent developments in computer hardware, software and broad-band internet connectivity, that the construction of this telescope, the calibration of the associated data and generation of high fidelity, high resolution wide-field images has become possible.

2. Science

The science case for LOFAR is broad and has several interesting applications outside the field of extra-solar astrophysics, such as studies of the Earth's ionosphere and the physical properties of the solar wind. For astrophysical research a number key scientific areas have been identified, which include:

- the sources and epoch of reionisation;
- the formation and evolution of galaxies and AGN;
- the nature of transient sources and high energy objects, and
- the origin of high energy cosmic rays.

We will discuss these in turn.

2.1. *Epoch of reionisation*

One of the most exciting goals of LOFAR will be to chart the end of the “Dark Ages” when the first stars and AGNs started to ionise the neutral baryonic gas pervading the Universe. In the joint discussion at this Texas symposium Madau has extensively discussed the theoretical models and observational status of this “epoch of reionisation”.

LOFAR's ability to search for and study the redshifted 21cm emission line at the redshift range of $z \sim 5-15$ will open up a window onto (literally) one of the most exciting periods in cosmic history. Furthermore, LOFAR will be able to carry out these studies with an angular resolution an order of magnitude better than WMAP. Towards the end of this decade the JWST and ALMA will begin directed studies of individual objects beyond $z = 7$. However, the field of view will be very small, and the number of observable objects in or before the Epoch of Reionisation (EoR) will be few. This will limit the usefulness of these instruments for the study of the large-scale distribution of HI and HII, ‘the raw stuff from which stars and galaxies are made’. Topics that LOFAR will address include:

- The history of reionisation, i.e. the redshift range in which the bulk of the HI became ionized. Identification of possible different stages of the process.
- The spatial distribution of ionised and neutral IGM, and its evolution during the epoch of reionisation.
- The objects responsible for reionising the Universe. Proto-galaxies and their massive stellar populations are the most likely sources, but the role of the first generation of quasars remains unclear.

2.2. *Galaxy formation and evolution*

One of the most intriguing problems in modern astrophysics concerns the formation of massive black holes, galaxies and clusters of galaxies. There are three main classes of objects in the early Universe that will be observed by LOFAR with the goal of investigating questions related to the formation of these objects. These key types of objects are (i) distant radio sources, produced by black holes in the nuclei of massive galaxies, (ii) “starburst” galaxies, i.e. infant galaxies observed to be undergoing a vigorous episode of star formation and (iii) diffuse radio emission as probes of gas in clusters of galaxies.

The most efficient method for finding *distant radio galaxies* uses an empirical correlation between radio spectral steepness and distance (e.g. de Breuck et al. 2000). Using this relation, LOFAR will efficiently pick out radio galaxies at larger distances than currently possible. Study of these distant radio galaxies at other wavelengths will provide information about the formation of massive galaxies and AGN. Furthermore, since distant radio galaxies pinpoint proto-clusters, studying the environment of these distant galaxies will constrain the formation of clusters at the earliest epochs (e.g. Venemans et al. 2002). It is possible that some of these radio galaxies are located at an epoch before reionisation has completely occurred. This would open up the possibility of studying the epoch of reionisation through observations of the absorbing neutral gas against these very distant radio galaxies (Carilli et al. 2002)

With its unprecedented sensitivity to non-thermal radio emission from star formation, LOFAR will detect large numbers of *star-forming galaxies* at an epoch at which the bulk of galaxy formation is believed to occur. Since the ratio of radio flux to sub-mm flux is a sensitive redshift indicator (Carilli and Yun 1999), LOFAR surveys, in combination with data from new far-IR and millimeter facilities such as SIRTf, ALMA, and JWST, will provide distances and thus allow for a complete census of the cosmic star-formation history, unhindered by the effects of dust obscuration.

Clusters of galaxies often contain diffuse radio sources that are shaped by the dynamics of the gas in which they are embedded, LOFAR will be able to detect and study these radio sources in the many tens of thousands of clusters up to redshifts of two that will be detected using the XMM X-ray telescope, the Planck satellite, and the Sloan Digital Sky Survey (e.g. Enßlin, T. A. and Röttgering, 2002). Such studies will be very relevant for (i) understanding the dynamics of the cluster gas (ii) determining the

origin of their magnetic field content, and (iii) constraining physical models for the, as yet unknown, origin of these sources.

2.3. *The bursting and transient universe*

LOFAR's large instantaneous beam, will make it uniquely suited to efficiently monitor a large fraction of the sky, allowing for the first time a sensitive unbiased survey for radio transients on a variety of time scales, ranging from a few tenths of seconds to many days. Rapid follow up with LOFAR at high resolution will provide accurate positions required for optical and X-ray identifications. Table 1 gives an overview of the classes of object known or expected to exhibit variable radio emission. Also indicated are the variability time-scales, the number of objects/events expected to be observed per year and an estimate of the distances to which these objects can be seen.

Table 1. Overview of transients expected to be detected and monitored with LOFAR. Also indicated are the variability time-scales, the number of objects/events expected to be observed per year and an estimate of the distances to which these objects can be seen.

Object	Variability Timescale	No. of Events	Maximum Distance
Radio Supernovae	days–months	$\sim 3/\text{yr}$	$2\text{--}3 \times \text{Virgo Cluster}$
GRB Afterglows	days–months	$\sim 100/\text{yr}$	Observable Universe
Galactic Black Holes and Neutron Stars	days–months	10–100/yr	Local Group
Pulsars	millisec–sec	few 1000	Whole Galaxy, M31
Intermediate mass Black Holes	days?	1–5/yr	Virgo Cluster
Exoplanets	minutes–hours	10–100	30 pc
Flare Stars	millisec–hours	100–1000	$< 1 \text{ kpc}$
‘LIGO Events’	$\leq \text{millisec}$	few?	Observable Universe

As can be seen from Table 1, for high energy astrophysics there are a number of particular interesting applications. From the empirical relation between radio and X-ray emission for Gamma-ray bursters and Galactic black-hole/neutron-star it is clear that the all-sky monitoring with LOFAR will be a factor of 5–10 more effective in discovering such events than previous all-sky-monitors. It is therefore anticipated that LOFAR will be the primary source of triggers for the high-energy community utilising target-of-opportunity programs on e.g. HST / VLT / Chandra / XMM etc. Further-

more, several models for strong ‘LIGO events’, for example the coalescence of two neutron stars, are predicted to have an associated strong burst of radio emission (e.g. Hansen and Lyutikov 2000). Similarly, prompt radio emission is predicted by some GRB models.

2.4. LOFAR as a cosmic ray detector

The existence of high-energy cosmic rays (HECRs) at energies between 10^{15} – $10^{20.5}$ eV is an outstanding challenge for particle astrophysics. Both the sites and processes for accelerating particles are unknown. Possible candidate sources of these HECRs are shocks in radio lobes of powerful radio galaxies, intergalactic shocks created during the epoch of galaxy formation, so-called Hyper-novae, Gamma-ray bursts and magnetars. Alternatively, HECRs are perhaps decay products of super-massive particles from topological defects, left over from phase transitions in the early universe.

A primary CR induces a particle cascade in the atmosphere which is aligned along the direction of motion of the primary particle. A substantial part of such a “CR shower” is leptonic and produces coherent radio emission (e.g. Cherenkov emission, transition radiation, and synchrotron emission) in the terrestrial magnetosphere. At the high Lorentz factors considered here, the cascade is confined to a slab a few meters wide perpendicular to the travel direction, which emits coherent ‘geo-synchrotron’ radiation below 200 MHz (e.g. Falcke and Gorham 2002). From the arrival times and intensities of the radio pulse at various antennas of LOFAR, the direction of the primary particle can then be determined to an accuracy of 1 degree.

LOFAR has a unique potential for studies of HECRs, including:

- The study of HECRs in the wide energy range from 10^{15} eV to $10^{20.5}$ eV with one and the same instrument; The standard optical methods (Cherenkov or fluorescence) which have only a 10% duty cycle, observe only a relative narrow range of particle energies;
- Investigating the poorly understood development of the electromagnetic part of the cascade by *in situ* radio observations; measurement of the height of the shower maximum, the forward cross-sections and inelasticity parameter in high energy particle collisions which cannot be determined in a particle collider.
- The discovery of point-sources in high-energy ($> 10^{18}$ eV) neutrons which can cross the Galaxy before they decay, and whose observation may thus reveal their origin. Discrimination between anisotropies caused by charged nuclei whose paths are affected by



Figure 1. An artist impression of the candidate layout of (a Netherlands version of) an individual LOFAR station.

the Galactic magnetic field and neutrons is, in principle, possible by studying the absence or presence of such anisotropies at lower energies;

- Measurement of the composition of HECRs from the study of simultaneous pairs of showers at a distance up to several 100 km. Such ‘multiplet’ events are expected from photodisintegration of CRs in the solar radiation field (Gerasimova-Zatsepin effect);
- Detection of coherent radio emission from neutrinos at energies $10^{15} - 10^{18}$ eV in horizontal showers, and of tau neutrino events (‘double-bang’: two showers at 50 km distance).

3. The telescope

LOFAR will have 2 antenna systems, one for the 10-90 MHz range, and one for the 110-240 MHz range. The antennas will be placed in soccer-field sized stations yielding, for each station, effective apertures that will range from 50 m to 150 m, depending on frequency. For an artist impression of (the Netherlands version of) such a station see Fig. 1.

The signals from each antenna are digitised and fed into the station beamformer. The beamformer can produce up to eight coherent “station-beams” within the primary power pattern of the antenna element in use.

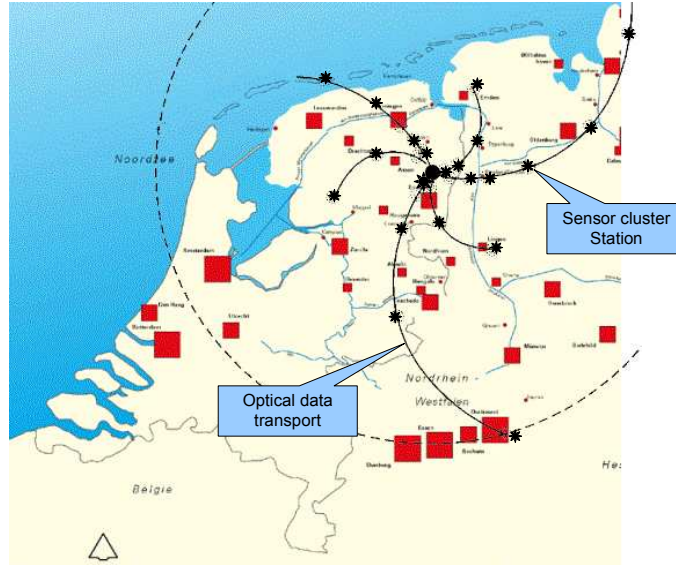


Figure 2. The approximate layout of the LOFAR stations in a 6-armed log-spiral pattern for the proposed Dutch site. (two other sites are also under consideration, for further info see text).

The output data stream from each station beam is sent to an optical link for transmission to the central processing facility.

In total, of the order of 100 stations will make up the array. These stations will be distributed over an area with a diameter of about 400 km (see Fig. 2). This yields a maximum angular resolution of about 0.6 arcseconds at the highest LOFAR frequencies.

An iterative scheme based on existing successful self-calibration techniques for radio astronomy will be used to calibrate LOFAR data. This scheme, which is currently under development, will solve for the ionospherically induced phase fluctuations, the characteristics of the station beams and maps of the radio sky. Furthermore, the removal of radio frequency interference is an important issue. This is facilitated by the high spectral resolution of LOFAR for which only a few percent of the spectrum is affected by RFI. Finally, the foreseen enormous data rates of maximally 25 Tb/s are a major challenge. However, this makes LOFAR an interesting testbed for ICT research and development, which in turn is helping to fund the instrument.

8 REFERENCES

4. The Project

ASTRON (Dwingeloo, the Netherlands), M.I.T. (Cambridge, USA) and the Naval Research Lab (Washington, USA) are responsible for the design, construction, operation and software of the LOFAR telescope. The schedule as agreed by the international LOFAR partners for the design and construction of LOFAR is given in Table 2.

Table 2. Schedule for the entire LOFAR project

Year	Milestone
2003	Integrated test station with 100 antenna
2005	LOFAR core operational
2006	Initial operations of central core plus first outer stations
2008	Full operation

A site characterisation committee is presently obtaining data needed to assess the suitability of LOFAR siting in the Netherlands, south-west Australia and the southern USA (Texas and New Mexico). A decision on the location for LOFAR is foreseen to be taken in 2003.

The international project is supervised by an International Steering Committee (ISC), consisting of directors of the participating institutes. An Engineering Consortium (EC) is responsible for the design and implementation of the instrument. The Science Consortium Board (SCB) is responsible for developing the science case for LOFAR in close collaboration with the community and gives scientific input to the EC.

The Science Consortium Board very much welcomes suggestions for improving or optimising the design of the instrument for general or very specific applications. For further information, visit: www.LOFAR.org

References

- Carilli, C. L., Gnedin, N. Y., and Owen, F.: 2002, *ApJ* **577**, 22
 Carilli, C. L. and Yun, M. S.: 1999, *ApJ* **513**, L13
 De Breuck, C., Röttgering, H., Miley, G., van Breugel, W., and Best, P.: 2000, *A&A* **362**, 519
 Enßlin, T. A. and Röttgering, H.: 2002, *A&A* **396**, 83
 Falcke, H. and Gorham, P.: 2002, *astro-ph/0207226*
 Hansen, B. M. S. and Lyutikov, M.: 2001, *MNRAS* **322**, 695
 Venemans, B. P., Kurk, J. D., Miley, G. K., Röttgering, H. J. A., et al. : 2002, *ApJ* **569**, L11